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Synergistic effects of plant growth regulators and micro-nutrients on harvest index and productivity of rice (*Oryza sativa* L.)

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Abstract

Panicle production and reproductive efficiency are major determinants of rice productivity under high-rainfall, lateritic soil conditions. A field experiment was conducted during the *kharif* seasons of 2023 and 2024 at the Education & Research Farm, Department of Agricultural Botany, Dr. BSKKV, Dapoli, Maharashtra, to evaluate the effect of foliar application of plant growth regulators (PGRs) and micronutrients on yield attributes and grain yield of rice (*Oryza sativa* L.). The experiment was laid out in a factorial randomized block design with four PGR treatments [Control, Indole-3-acetic acid (IAA) @ 50 ppm, 6-Benzyl aminopurine (6-BA) @ 75 ppm, and Paclobutrazol (PBZ) @ 100 ppm] and three micronutrient treatments [Control, Boron @ 0.2%, and Zinc @ 0.3%], replicated thrice. Foliar sprays were imposed at primordial initiation and flowering stages. Results revealed that foliar application of IAA @ 50 ppm significantly enhanced panicle length (27.50 cm), number of spikelets per panicle (182.64), spikelet fertility (88.11%), grain yield per plant (22.66 g), and grain yield per hectare (55.42 q ha⁻¹) in pooled analysis, closely followed by 6-BA @ 75 ppm. Among micronutrients, Zinc @ 0.3% recorded significantly higher spikelet fertility (86.93%), grain yield per plant (21.83 g), and grain yield per hectare (53.79 q ha⁻¹) compared to Boron and control. Interaction effects indicated that IAA @ 50 ppm combined with Zinc @ 0.3% produced the highest grain yield per plant (22.66 g) and grain yield per hectare (55.42 q ha⁻¹), along with superior spikelet fertility (88.11%), followed by 6-BA + Zinc. Paclobutrazol treatments were comparatively inferior for most reproductive and yield traits. The study demonstrates that foliar application of IAA @ 50 ppm or 6-BA @ 75 ppm in combination with Zinc @ 0.3% is an effective strategy for improving panicle development, reproductive efficiency, and grain yield of rice under high-rainfall lateritic soil ecosystems.

Keywords: Rice, productivity, harvest index, spikelet fertility, plant growth regulators, indole-3-acetic acid, 6-benzyl aminopurine, zinc, boron grain yield

1. Introduction

Rice (*Oryza sativa* L.) is a principal staple food for more than half of the world's population and plays a crucial role in ensuring food security in India. Although India is one of the leading rice-producing countries, productivity in several regions remains below potential due to biotic and abiotic stresses, nutrient imbalances, and suboptimal crop management practices. These constraints are particularly severe in high-rainfall ecosystems. In the Konkan region of Maharashtra, characterized by heavy rainfall and lateritic soils, rice cultivation faces challenges such as nutrient leaching, poor root aeration, reduced tillering, and low spikelet fertility, ultimately resulting in lower grain yield. Conventional soil fertilization is often inefficient under such conditions, necessitating alternative approaches to improve nutrient use efficiency and crop performance.

Foliar application of plant growth regulators (PGRs) and micronutrients has emerged as an effective strategy to enhance growth and reproductive efficiency in rice. Auxins such as Indole-3-acetic acid (IAA) promote root growth and tillering, cytokinin like 6-Benzyl aminopurine (6-BA) enhance panicle differentiation and delay senescence, while Paclobutrazol (PBZ) regulates plant architecture and stress tolerance. Among micronutrients, zinc (Zn) is involved in enzyme activation, chlorophyll synthesis, and pollen viability, whereas boron (B) plays a key role in

carbohydrate translocation and fertilization. Deficiencies of Zn and B are common in lateritic soils and are closely associated with reduced spikelet fertility and grain yield. Previous studies have reported that combined application of PGRs and micronutrients may produce synergistic effects by improving source-sink relationships, assimilate partitioning, and reproductive success. However, limited information is available on their integrated use under high-rainfall lateritic soil conditions of the Konkan region. Therefore, the present investigation was undertaken to evaluate the interactive effects of foliar-applied PGRs (IAA, 6-BA, and PBZ) and micronutrients (Zn and B) on growth, yield attributes, grain yield, and harvest index of rice under high-rainfall ecosystems, with the objective of identifying effective combinations for enhancing productivity.

2. Materials and Methods

The field experiment entitled “Effect of Plant Growth Regulators and Micronutrients on Morpho-Physiological Traits, Growth and Yield of Rice (*Oryza sativa* L.)” was conducted during the *kharif* seasons of 2023 and 2024 at the Education and Research Farm, Department of Agricultural Botany, College of Agriculture, Dapoli, Maharashtra, India. The experimental site is situated at 17°45' N latitude and 73°11' E longitude, at an altitude of approximately 250 m above mean sea level. The region is characterized by a tropical humid climate with heavy rainfall ranging from 4000 to 4300 mm during the crop season. The mean temperature during the growing period ranged from 22 to 34°C with consistently high relative humidity. The soil of the experimental field was lateritic in nature, belonging to the Gimhavana soil series (Fluventic Ustropepts). Composite soil samples collected from 0–22.5 cm depth prior to transplanting were analyzed following standard procedures. The soil was slightly acidic in reaction (pH 5.5), medium in available nitrogen (179 kg ha⁻¹), low in available phosphorus (8.54 kg ha⁻¹), and high in available potassium (383 kg ha⁻¹). The soil was found to be deficient in zinc (0.23 mg kg⁻¹) and boron (0.26 mg kg⁻¹). The experiment was laid out in a Factorial Randomized Block Design (FRBD) comprising twelve treatment combinations replicated thrice. Treatments consisted of four levels of plant growth regulators and three levels of micronutrients. The plant growth regulator treatments were G₀ – Control (no PGR), G₁ – Indole-3-acetic acid (IAA) @ 50 ppm, G₂ – 6-Benzyl aminopurine (6-BA) @ 75 ppm, and G₃ – Paclobutrazol (PBZ) @ 100 ppm. The micronutrient treatments included M₀ – Control (no micronutrient), M₁ – Boron @ 0.2%, and M₂ – Zinc @ 0.3%. The rice variety Ratnagiri-5 was used for the study. Twenty-five-day-old seedlings were transplanted at a spacing of

20 × 15 cm. A recommended fertilizer dose of 100:50:50 kg N:P₂O₅:K₂O ha⁻¹ was applied uniformly to all plots. Foliar application of plant growth regulators and micronutrients was carried out twice during the crop growth period. The first spray was applied at 60 days after sowing (DAS) corresponding to the primordial initiation stage, and the second at 80 DAS during the flowering stage. The required concentrations were prepared using distilled water and applied uniformly with a knapsack sprayer during morning hours to facilitate better absorption. All recommended agronomic practices were followed uniformly across treatments. Irrigation was maintained at shallow water depth throughout the growing period. Manual weeding was carried out as and when necessary. No severe incidence of pests or diseases was observed during the experimental period. Five plants were randomly selected and tagged in each plot for recording observations. Morphological parameters such as plant height, number of tillers per plant, number of leaves per plant, dry matter accumulation in root, stem, leaf and panicle, and total dry matter production were recorded at 50, 75, 100 DAS and at harvest. Yield attributes including number of panicles per plant, spikelet fertility, grain yield per plant, total biomass, harvest index and grain yield per hectare were recorded at harvest. The data recorded during both years were subjected to analysis of variance (ANOVA) appropriate to the Factorial Randomized Block Design as described by Statistical Methods for Agricultural Workers. Treatment means were compared using the Critical Difference (CD) test at the 5 per cent level of significance.

3. Results and Discussion

The observations recorded were analyzed statistically and presented and discussed under the following heads:

3.1 Effect of Plant growth regulators on Yield and Yield attributes

3.1.1 Effect of plant growth regulators on no. of panicles per plant in rice

Foliar application of plant growth regulators significantly influenced the number of panicles per plant during both the years and in pooled analysis (Table 1). The significantly higher number of panicles per plant was recorded with PBZ @ 100 ppm (G₃) (19.01, 17.47 and 18.24 during 2023, 2024 and pooled data, respectively), which was statistically at par with 6-BA @ 75 ppm (G₂) (17.68 pooled) and IAA @ 50 ppm (G₁) (17.56 pooled), and significantly superior to the control (15.37 pooled). The lowest number of panicles per plant was observed under no application of PGRs (G₀).

Table 1: Effect of plant growth regulators and micronutrients on No of panicles per plant & spikelet fertility (%) in rice during *kharif* 2023, 2024 & pooled analysis

Sr. No.	Treatments	No. of panicles per plant			Spikelet fertility (%)		
		2023	2024	Pooled	2023	2024	Pooled
(A)	Foliar application of plant growth regulators						
G ₀	No application of PGRs	15.88	14.86	15.37	73.93	72.48	73.21
G ₁	IAA @ 50 ppm	18.19	16.92	17.56	85.52	84.02	84.77
G ₂	6-BA @ 75ppm	18.28	17.07	17.68	83.87	83.02	83.44
G ₃	PBZ @ 100 ppm	19.01	17.47	18.24	75.37	74.39	74.88
	SE (m) ±	0.07	0.06	0.04	0.32	0.32	0.21
	CD at 5%	0.19	0.18	0.13	0.93	0.94	0.62
(B)	Foliar application of micronutrients						
M ₀	No application of MNTs	17.29	15.87	16.58	75.48	75.03	75.25
M ₁	Boron @ 0.2%	17.91	16.64	17.27	81.10	79.04	80.07
M ₂	Zinc @ 0.3%	18.33	17.24	17.78	82.44	81.37	81.91

	SE (m) ±	0.06	0.05	0.04	0.27	0.28	0.18
	CD at 5%	0.17	0.16	0.11	0.80	0.81	0.54
(C)	Interaction (G x M)						
	SE (m) ±	0.11	0.11	0.07	0.55	0.55	0.37
	CD at 5%	0.33	0.31	0.21	1.56	1.59	1.05
	GM	17.84	16.58	17.21	79.67	78.48	79.07

The increase in panicle number under PGR treatments may be attributed to improved tiller differentiation, enhanced panicle initiation, and better assimilate partitioning towards reproductive sinks. Auxin (IAA) promotes tiller survival and panicle initiation by regulating cell division and elongation, while cytokinin (6-BA) stimulate axillary bud growth and delay senescence, thereby supporting higher panicle formation. Paclobutrazol, by restricting excessive vegetative growth, may have redirected assimilates towards reproductive development, resulting in a higher number of productive panicles. These results are in conformity with Kumar *et al.* (2018) ^[5], who reported increased panicle number with foliar application of IAA, and Martínez *et al.* (2021) ^[7], who observed enhanced panicle formation with IAA and 6-BA treatments. Similar improvements in panicle number contributing to higher yield were also reported by Renuka *et al.* in rice under stress conditions.

3.1.2 Effect of plant growth regulators on spikelet fertility in rice

Among the plant growth regulators, foliar application of IAA @ 50 ppm (G₁) recorded the significantly highest spikelet fertility (Table 1: 85.52, 84.02 and 84.77% during 2023, 2024 and pooled data, respectively), which was at par with 6-BA @ 75 ppm (G₂) (83.87, 83.02 and 83.44%) and significantly superior

to the control (73.21%). The lowest spikelet fertility was observed under PBZ @ 100 ppm (G₃) with pooled mean of 74.88%.

The enhancement in spikelet fertility under IAA and 6-BA treatments may be attributed to reduced floret abortion, improved pollen viability, and efficient assimilate translocation during anthesis and grain-setting stages. Auxins enhance fertilization efficiency and sink strength, while cytokinin delay senescence and support spikelet development by maintaining hormonal balance during reproductive growth. These results are in close conformity with the findings of Wei *et al.* (2016) ^[18] and Chen *et al.* (2016) ^[2], who reported significant improvements in spikelet fertility and grain number with foliar application of 6-BA. Similarly, Kumar *et al.* (2023) observed a substantial increase in spikelet fertility in rice following exogenous IAA application under stress conditions.

3.1.3 Effect of plant growth regulators on grain yield (g) per plant in rice

Among the plant growth regulators, foliar application of IAA @ 50 ppm (G₁) recorded significantly higher grain yield per plant (Table 2: 22.37, 21.31 and 21.84 g during 2023, 2024 and pooled data, respectively) compared to the control (18.82 g pooled).

Table 2: Effect of plant growth regulators and micronutrients on Grain yield (g) per plant & Total biomass (g) /plant in rice during *kharif* 2023, 2024 & pooled analysis

Sr. No.	Treatments	Grain yield (g) per plant			Total biomass (g) /plant		
		2023	2024	Pooled	2023	2024	Pooled
(A)	Foliar application of plant growth regulators						
G ₀	No application of PGRs	19.36	18.28	18.82	59.52	57.10	58.31
G ₁	IAA @ 50 ppm	22.37	21.31	21.84	67.41	64.47	65.94
G ₂	6-BA @ 75ppm	21.87	20.74	21.31	66.29	63.27	64.78
G ₃	PBZ @ 100 ppm	20.49	19.30	19.90	63.41	60.31	61.86
	SE (m) ±	0.12	0.11	0.09	0.17	0.14	0.11
	CD at 5%	0.36	0.32	0.26	0.48	0.41	0.31
(B)	Foliar application of micronutrients						
M ₀	No application of MNTs	20.23	19.21	19.72	61.11	59.07	60.09
M ₁	Boron @ 0.2%	21.21	19.89	20.55	65.11	61.77	63.44
M ₂	Zinc @ 0.3%	21.64	20.63	21.13	66.25	63.02	64.63
	SE (m) ±	0.11	0.10	0.08	0.14	0.12	0.09
	CD at 5%	0.31	0.28	0.22	0.42	0.35	0.27
(C)	Interaction (G x M)						
	SE (m) ±	0.21	0.19	0.15	0.29	0.24	0.18
	CD at 5%	0.61	0.55	0.44	0.82	0.69	0.53
	GM	21.02	19.91	20.47	64.16	61.29	62.72

The treatment was closely followed by 6-BA @ 75 ppm (G₂), which produced a pooled grain yield of 21.31 g per plant and was statistically at par with IAA. Application of PBZ @ 100 ppm (G₃) resulted in a moderate improvement in grain yield (19.90 g pooled), but remained significantly inferior to IAA and 6-BA treatments. The higher grain yield under IAA and 6-BA treatments can be attributed to improved source-sink relationships, enhanced translocation of photosynthates, increased spikelet fertility, and efficient grain filling. Auxin application promotes cell division, tiller survival, and assimilate

movement towards developing grains, whereas cytokinin delay leaf senescence and enhance sink strength during the reproductive phase. These findings are in strong agreement with Ruchitha *et al.* (2020) ^[15], who reported a significant increase in rice grain yield per plant with IAA @ 50 ppm due to improved tillering and grain filling. Similarly, Pan *et al.* (2021) ^[10] and Renuka *et al.* (2024) observed substantial yield enhancement in rice following foliar application of 6-BA, attributing the response to improved panicle development and spikelet fertility.

3.1.4 Effect of plant growth regulators on total biomass (g) /plant in rice

Among the plant growth regulators, foliar application of IAA @ 50 ppm (G_1) resulted in the significantly highest total biomass per plant (Table 2: 67.41, 64.47 and 65.94 g during 2023, 2024 and pooled data, respectively), followed by 6-BA @ 75 ppm (G_2), which recorded a pooled biomass of 64.78 g per plant. Both these treatments were significantly superior to the control (58.31 g pooled). Application of PBZ @ 100 ppm (G_3) also improved biomass accumulation (61.86 g pooled) over the control, though its effect was comparatively lower than IAA and 6-BA.

The enhanced biomass production under IAA application may be attributed to stimulation of cell division and elongation, increased leaf area development, and improved photosynthetic efficiency, resulting in greater dry matter accumulation. These observations are in close conformity with the findings of Shahi *et al.* (2023) ^[16], who reported a 22–25% increase in vegetative dry biomass of hybrid rice with foliar application of IAA @ 50 ppm. Similarly, the positive response to 6-BA observed in the present study aligns with the findings of Pan *et al.* (2023), who reported significant improvements in total plant dry matter following foliar application of 6-BA, attributed to delayed leaf senescence and sustained photosynthetic activity due to enhanced antioxidant enzyme activity.

3.1.5 Effect of plant growth regulators on harvest index (%) in rice

Among the plant growth regulator treatments, foliar application of IAA @ 50 ppm (G_1) recorded the significantly highest harvest index (Table 3: 33.20, 33.06 and 33.13% during 2023, 2024 and pooled data, respectively), which was at par with 6-BA @ 75 ppm (G_2) (32.89% pooled) and significantly superior to the control (32.27%). Application of PBZ @ 100 ppm (G_3) resulted in the lowest harvest index (32.17% pooled), which was statistically comparable with the control.

The improvement in harvest index under IAA and 6-BA treatments suggests more efficient translocation and partitioning of assimilates towards grain formation rather than vegetative biomass. Auxin application enhances sink strength by promoting panicle development and grain filling, while cytokinin delay leaf senescence and sustain photosynthetic activity during the reproductive phase, thereby increasing grain dry matter accumulation. These findings are in close agreement with Li *et al.* (2019), who reported a significant increase in harvest index with foliar application of 6-BA due to enhanced grain-setting rate and spike dry weight. Similarly, Shahi *et al.* (2023) ^[16] observed a substantial improvement in harvest index in rice with foliar application of IAA, attributing the response to more efficient assimilate allocation towards grain yield.

Table 3: Effect of plant growth regulators and micronutrients on harvest index & grain yield (q) per ha in rice during *kharif* 2023, 2024 & pooled analysis

Sr. No.	Treatments	Harvest index (%)			Grain yield (q) per ha		
		2023	2024	Pooled	2023	2024	Pooled
(A)	Foliar application of plant growth regulators						
G_0	No application of PGRs	32.53	32.01	32.27	45.40	43.39	44.39
G_1	IAA @ 50 ppm	33.20	33.06	33.13	53.45	49.84	51.64
G_2	6-BA @ 75ppm	33.00	32.78	32.89	52.37	49.20	50.78
G_3	PBZ @ 100 ppm	32.33	32.01	32.17	48.38	45.78	47.08
	SE (m) $\pm$	0.19	0.18	0.13	0.26	0.24	0.15
	CD at 5%	0.55	0.53	0.39	0.77	0.72	0.44
(B)	Foliar application of micronutrients						
M_0	No application of MNTs	33.09	32.49	32.79	48.04	45.48	46.76
M_1	Boron @ 0.2%	32.56	32.19	32.37	49.99	47.03	48.51
M_2	Zinc @ 0.3%	32.65	32.71	32.68	51.67	48.64	50.16
	SE (m) $\pm$	0.16	0.16	0.12	0.23	0.21	0.13
	CD at 5%	NS	NS	0.34	0.67	0.62	0.38
(C)	Interaction (G x M)						
	SE (m) $\pm$	0.33	0.31	0.23	0.46	0.42	0.26
	CD at 5%	NS	0.89	NS	1.31	1.21	0.75
	GM	32.76	32.46	32.61	49.90	47.05	48.48

3.1.6 Effect of plant growth regulators on grain yield (q) per ha in rice

Among the plant growth regulator treatments, foliar application of IAA @ 50 ppm (G_1) recorded the significantly highest grain yield (Table 3: 53.45, 49.84 and 51.64 q ha⁻¹ during 2023, 2024 and pooled data, respectively), which was at par with 6-BA @ 75 ppm (G_2) (50.78 q ha⁻¹ in pooled data) and significantly superior to the control (44.39 q ha⁻¹).

Application of PBZ @ 100 ppm (G_3) resulted in comparatively lower grain yield (47.08 q ha⁻¹ pooled), though it remained significantly better than the untreated control. The enhanced grain yield under IAA and 6-BA treatments may be attributed to improved panicle initiation, higher spikelet fertility, reduced floret abortion and more efficient assimilate partitioning towards grains. Auxin application enhances sink strength by promoting cell division and elongation during reproductive development, while cytokinin delay leaf senescence, sustain photosynthetic

activity and improve grain filling. These results are in close conformity with Zheng *et al.* (2018), who reported significant yield enhancement in wheat due to foliar application of 6-BA through reduced floret abortion and increased grain number. Similarly, Shahi *et al.* (2023) ^[16] observed a substantial improvement in grain yield of rice with foliar application of IAA @ 50 ppm, attributing the response to improved yield components and higher harvest index.

3.2 Effect of Micronutrients on Yield and Yield Attributes

3.2.1 Effect of micronutrients on no. of panicles per plant in rice

Foliar application of micronutrients significantly increased the number of panicles per plant during both the years and in pooled data (Table 1). Application of zinc @ 0.3% (M_2) recorded the highest number of panicles per plant (18.33, 17.24 and 17.78 during 2023, 2024 and pooled data, respectively), followed by

boron @ 0.2% (M_1) (17.27 pooled), both being significantly superior to the no-micronutrient control (16.58 pooled). The improvement in panicle number due to zinc and boron application may be attributed to enhanced tiller survival, improved nutrient translocation, and strengthened reproductive organ development. Zinc plays a key role in chlorophyll synthesis, enzyme activation, and auxin metabolism, which collectively promote tillering and panicle initiation. Boron is essential for cell wall formation, meristematic activity, and translocation of photosynthates, thereby supporting the development of more productive panicles. These findings are in close agreement with Rout and Das (2015) ^[14], who reported increased panicles per hill with foliar boron application, and Singh *et al.* (2018), who observed significant enhancement in panicle number following zinc application in rice.

3.2.2 Effect of micronutrients on spikelet fertility in rice

Foliar application of micronutrients also exerted a significant effect on spikelet fertility in rice. Application of zinc @ 0.3% (M_2) resulted in the highest spikelet fertility (Table 1: 82.44, 81.37 and 81.91% during 2023, 2024 and pooled data, respectively), followed by boron @ 0.2% (M_1) (80.07% pooled), both of which were significantly superior to the no-micronutrient control (75.25%). The increase in spikelet fertility due to zinc and boron application may be attributed to their critical roles in pollen development, pollen tube growth, and fertilization processes. Zinc is involved in enzyme activation, auxin metabolism, and carbohydrate utilization, while boron enhances pollen viability, stigma receptivity, and translocation of assimilates to developing spikelets. These findings are in agreement with Shivay *et al.* (2008) and Raghuveer Rao *et al.* (2013) ^[13], who reported reduced spikelet sterility and improved grain setting in rice with foliar application of zinc and boron.

3.2.3 Effect of micronutrients on grain yield (g) per plant in rice

Foliar application of micronutrients significantly improved grain yield per plant over the no-micronutrient control. Application of zinc @ 0.3% (M_2) recorded the highest grain yield (Table 2: 21.64, 20.63 and 21.13 g during 2023, 2024 and pooled data, respectively), followed by boron @ 0.2% (M_1) with a pooled mean of 20.55 g per plant. Both micronutrient treatments were significantly superior to the control (19.72 g pooled). The increase in grain yield due to zinc and boron application may be attributed to their essential roles in enzymatic activity, photosynthesis, carbohydrate metabolism, and reproductive development. Zinc enhances chlorophyll synthesis, auxin metabolism, and grain filling efficiency, while boron is crucial for pollen viability, fertilization, and translocation of assimilates to developing grains. These results corroborate the findings of Meena *et al.* (2020) ^[9], who reported significant increases in grain yield per plant with foliar application of zinc and boron, individually as well as in combination, due to improved physiological efficiency and reproductive success.

3.2.4 Effect of micronutrients on total biomass (g) /plant in rice

Foliar application of micronutrients significantly enhanced total biomass production over the no-micronutrient control. Application of zinc @ 0.3% (M_2) recorded the highest total biomass (Table 2: 66.25, 63.02 and 64.63 g during 2023, 2024 and pooled data, respectively), followed closely by boron @ 0.2% (M_1) with a pooled mean of 63.44 g per plant. Both

micronutrient treatments were significantly superior to the control, which recorded the lowest biomass (60.09 g pooled). The increase in total biomass due to zinc and boron application can be attributed to their essential roles in chlorophyll synthesis, enzyme activation, photosynthetic efficiency, and nutrient uptake. Zinc improves carbohydrate metabolism and auxin synthesis, while boron enhances cell wall development, meristematic activity, and assimilate translocation. These results are well supported by Meena *et al.* (2017) ^[8], who reported a substantial increase in total biomass with combined foliar application of zinc and boron, and by Prasad *et al.* (2019) ^[12], who observed a 25% increase in rice biomass following zinc and boron supplementation.

3.2.5 Effect of micronutrients on harvest index (%) in rice

Foliar application of micronutrients showed a marginal but significant effect on harvest index in pooled analysis (Table 3). Application of zinc @ 0.3% (M_2) recorded the highest pooled harvest index (32.68%), followed by the control (32.79%) and boron @ 0.2% (M_1) (32.37%). However, the differences among micronutrient treatments were non-significant during individual years, indicating a relatively stable harvest index across micronutrient levels. The slight improvement in harvest index with zinc application may be attributed to enhanced photosynthetic efficiency, improved enzyme activity, and better grain filling, resulting in proportionately higher grain yield relative to total biomass. These results corroborate the findings of Fageria and Baligar (2007) ^[3], who reported consistent improvements in harvest index of rice following foliar zinc application, along with substantial increases in grain yield. The role of boron in improving harvest index through enhanced reproductive development and assimilate utilization has also been reported by Bayar *et al.* (2024) ^[11], although its effect in the present study was comparatively less pronounced.

3.2.6 Effect of micronutrients on grain yield (q) per ha in rice

Foliar application of micronutrients significantly influenced grain yield per hectare during both years and in pooled analysis (Table 3). Application of zinc @ 0.3% (M_2) recorded the highest grain yield (51.67, 48.64 and 50.16 q ha⁻¹ during 2023, 2024 and pooled data, respectively), followed by boron @ 0.2% (M_1) (48.51 q ha⁻¹ pooled), both of which were significantly superior to the no-micronutrient control (46.76 q ha⁻¹). The increase in grain yield with zinc application may be attributed to its role in enzyme activation, chlorophyll synthesis, auxin metabolism and improved spikelet fertility, leading to enhanced grain filling. Boron application improves pollen viability, pollen tube growth and fertilization efficiency, thereby increasing grain set and yield. These findings corroborate the results of Krishna *et al.* (2023) ^[4], who reported a substantial increase in rice grain yield following foliar application of ZnSO₄, and Sharma *et al.* (2023) ^[17], who observed a 10% improvement in grain yield with foliar boron application due to enhanced reproductive efficiency.

3.3 Interaction Effect of Plant growth regulators and Micronutrients

3.3.1 Interaction effect of PGRs & micronutrients on no. of panicles per plant in rice

The interaction between plant growth regulators (PGRs) and micronutrients significantly influenced the number of panicles per plant during both years and in pooled analysis (Table 4).

Table 4: Interaction effect of plant growth regulators and micronutrients on number of panicles per plant in rice

MNTs PGRs	No. of panicles per plant								
	2023			2024			Pooled		
	M ₀	M ₁	M ₂	M ₀	M ₁	M ₂	M ₀	M ₁	M ₂
G ₀	15.57	15.94	16.13	14.18	15.13	15.26	14.88	15.54	15.69
G ₁	17.54	18.17	18.85	16.10	16.95	17.72	16.82	17.56	18.29
G ₂	17.74	18.25	18.85	16.32	17.01	17.89	17.03	17.63	18.37
G ₃	18.29	19.26	19.48	16.86	17.48	18.07	17.57	18.37	18.78
SE (m) ±	0.11			0.11			0.07		
CD at 5%	0.33			0.31			0.21		

The interaction between plant growth regulators (PGRs) and micronutrients significantly influenced the number of panicles per plant during both years and in the pooled analysis (Table 4). Among the treatment combinations, PBZ @ 200 ppm with zinc (G₃M₂) recorded the highest number of panicles per plant (19.48, 18.07 and 18.78 during 2023, 2024 and pooled data, respectively), closely followed by PBZ @ 200 ppm with boron (G₃M₁) and 6-BA @ 75 ppm with zinc (G₂M₂). Overall, the combined application of PGRs along with zinc or boron proved superior over their individual or control treatments in enhancing panicle production in rice. These findings are in agreement with earlier reports highlighting the positive interaction of PGRs with micronutrients on panicle formation in rice and other cereals (Raghuveer Rao *et al.*, 2013) ^[13], thereby substantiating the present results.

3.3.2 Interaction effect of PGRs & micronutrients on spikelet fertility in rice

The interaction between plant growth regulators (PGRs) and micronutrients exerted a significant influence on spikelet fertility during both years and in pooled analysis (Table 5).

Table 5: Interaction effect of plant growth regulators and micronutrients spikelet fertility (%) in rice

MNTs PGRs	Spikelet fertility (%) in rice								
	2023			2024			Pooled		
	M ₀	M ₁	M ₂	M ₀	M ₁	M ₂	M ₀	M ₁	M ₂
G ₀	70.34	75.09	76.36	67.95	74.40	75.09	69.15	74.74	75.72
G ₁	81.26	86.68	88.62	81.08	83.39	87.60	81.17	85.04	88.11
G ₂	78.08	86.11	87.42	80.03	82.94	86.09	79.05	84.52	86.76
G ₃	72.24	76.51	77.35	71.05	75.42	76.70	71.64	75.97	77.03
SE (m) ±	0.55			0.55			0.37		
CD at 5%	1.56			1.59			1.05		

Among the treatment combinations, IAA @ 50 ppm with zinc (G₁M₂) recorded the highest spikelet fertility (88.62, 87.60 and 88.11% during 2023, 2024 and pooled data, respectively), closely followed by IAA @ 50 ppm with boron (G₁M₁) and 6-BA @ 75 ppm with zinc (G₂M₂). The lowest spikelet fertility was consistently observed under the control (G₀M₀) and PBZ-based combinations. The superior performance of IAA and 6-BA in combination with zinc or boron may be attributed to improved pollen viability, enhanced stigma receptivity and efficient assimilate partitioning towards reproductive sinks. Auxins and cytokinin promote reproductive organ development and delay spikelet senescence, while zinc and boron play critical roles in pollen formation, fertilization processes and hormonal regulation, thereby reducing spikelet sterility. These results corroborate earlier findings of enhanced spikelet fertility due to synergistic application of PGRs and micronutrients in rice, as reported by Raghuveer Rao *et al.* (2013) ^[13], Zhang *et al.* (2013)

^[20] and Khampuang *et al.* (2024), lending strong support to the present investigation.

3.3.3 Interaction effect of PGRs & micronutrients on grain yield (g) per plant in rice

The interaction between plant growth regulators (PGRs) and micronutrients significantly influenced grain yield per plant during both years and in pooled analysis (Table 6). Among the treatment combinations, IAA @ 50 ppm with zinc (G₁M₂) produced the highest grain yield (23.29, 22.03 and 22.66 g plant⁻¹ in 2023, 2024 and pooled data, respectively), followed by 6-BA @ 75 ppm with zinc (G₂M₂). The lowest grain yield was consistently recorded under the control treatment (G₀M₀) and PBZ-based combinations across seasons. The superior performance of IAA and 6-BA in combination with zinc can be attributed to improved source–sink balance, enhanced assimilate partitioning towards developing grains and better grain filling efficiency. Auxin- and cytokinin-mediated stimulation of sink strength, coupled with zinc-regulated enzymatic activity and carbohydrate metabolism, likely resulted in reduced spikelet sterility and increased grain weight per plant.

Table 6: Interaction effect of plant growth regulators and micronutrients grain yield (g) per plant in rice

MNTs PGRs	Grain yield (g) per plant								
	2023			2024			Pooled		
	M ₀	M ₁	M ₂	M ₀	M ₁	M ₂	M ₀	M ₁	M ₂
G ₀	19.16	19.34	19.57	17.50	18.52	18.81	18.33	18.93	19.19
G ₁	21.26	22.57	23.29	20.47	21.43	22.03	20.86	22.00	22.66
G ₂	20.76	22.23	22.63	19.96	20.36	21.91	20.36	21.29	22.27
G ₃	19.73	20.69	21.05	18.91	19.24	19.75	19.32	19.97	20.40
SE (m) ±	0.21			0.19			0.15		
CD at 5%	0.61			0.55			0.44		

These results are in close conformity with earlier findings where combined application of PGRs and micronutrients significantly enhanced grain yield in cereals. Similar synergistic effects of IAA or 6-BA with zinc or boron on grain yield have been reported by Patel *et al.* (2018), Kumar *et al.* (2019) and Zhang *et al.* (2021) ^[20], thereby lending strong support to the present investigation.

3.3.4 Interaction effect of PGRs & micronutrients on total biomass (g) /plant in rice

The interaction between plant growth regulators and micronutrients significantly influenced total biomass production during both years and in pooled analysis (Table 7). Among the treatment combinations, IAA @ 50 ppm with zinc (G₁M₂) recorded the highest total biomass (69.97, 66.87 and 68.42 g plant⁻¹ in 2023, 2024 and pooled data, respectively), followed closely by 6-BA @ 75 ppm with zinc (G₂M₂) and IAA @ 50 ppm with boron (G₁M₁). The lowest biomass accumulation was consistently observed under the control treatment (G₀M₀) across both seasons. The superior performance of IAA and 6-BA in combination with zinc may be attributed to synergistic enhancement of vegetative growth through auxin- and cytokinin-mediated cell division and elongation, coupled with zinc’s role in enzymatic activation, chlorophyll synthesis and improved photosynthetic efficiency. This interaction likely promoted greater tiller production, leaf area development and assimilate accumulation, resulting in higher total dry matter. Boron combinations, though beneficial, were comparatively less effective than zinc.

Table 7: Interaction effect of plant growth regulators and micronutrients total biomass (g) per plant in rice

MNTs PGRs	Total biomass (g) per plant								
	2023			2024			Pooled		
	M ₀	M ₁	M ₂	M ₀	M ₁	M ₂	M ₀	M ₁	M ₂
G ₀	58.02	60.07	60.46	56.04	57.18	58.06	57.03	58.63	59.26
G ₁	63.62	68.64	69.97	61.26	65.28	66.87	62.44	66.96	68.42
G ₂	62.51	67.39	68.97	60.23	64.02	65.57	61.37	65.70	67.27
G ₃	60.28	64.36	65.58	58.75	60.60	61.58	59.52	62.48	63.58
SE (m) ±	0.29			0.24			0.18		
CD at 5%	0.82			0.69			0.53		

These findings are in close agreement with earlier reports by Ruchitha *et al.* (2020) ^[15], Pan *et al.* (2021) ^[10] and Renuka *et al.* (2024), who also documented significant improvements in rice biomass due to interactive effects of PGRs—particularly IAA or 6-BA—with zinc, thereby supporting the results of the present investigation.

3.3.5 Interaction effect of PGRs & micronutrients on harvest index (%) in rice

The interaction between plant growth regulators and micronutrients showed a noticeable effect on Harvest Index (HI) in 2024 (Table 8). Among the combinations, IAA @ 50 ppm with zinc (G₁M₂) and 6-BA @ 75 ppm with zinc (G₂M₂) recorded the highest HI values (32.95% and 33.41%, respectively), while the lowest HI was observed in the control (G₀M₀, 31.23%) and PBZ-based combinations.

Table 8: Interaction effect of plant growth regulators and micronutrients harvest index (%) in rice

MNTs PGRs	Harvest index		
	2024		
	M ₀	M ₁	M ₂
G ₀	31.23	32.38	32.40
G ₁	33.41	32.83	32.95
G ₂	33.13	31.80	33.41
G ₃	32.19	31.75	32.08
SE (m) ±	0.31		
CD at 5%	0.89		

The enhanced HI under IAA or 6-BA with zinc can be attributed to improved assimilate partitioning, where a larger proportion of total biomass was directed toward grain formation rather than vegetative growth. Auxins and cytokinin stimulate sink strength by promoting grain filling, while zinc enhances enzymatic activities and hormonal regulation, facilitating efficient nutrient allocation. Boron combinations showed moderate improvements, but zinc consistently amplified the effect of PGRs. These results are consistent with earlier studies by Kumar and Singh (2020) ^[6], Zhang *et al.* (2021) ^[20], and Boonchuay *et al.* (2022), who reported that the combined application of PGRs (IAA or 6-BA) with zinc significantly improved HI by enhancing sink efficiency, hormonal balance, and nutrient allocation, particularly under conditions where micronutrients were limiting.

3.3.6 Interaction effect of PGRs & micronutrients on grain yield (q) per ha in rice

The interaction between plant growth regulators (PGRs) and micronutrients significantly influenced grain yield during both years and in pooled data (Table 9).

Table 9: Interaction effect of plant growth regulators and micronutrients grain yield (q) per hectare in rice

MNTs PGRs	Grain yield (q) per hectare								
	2023			2024			Pooled		
	M ₀	M ₁	M ₂	M ₀	M ₁	M ₂	M ₀	M ₁	M ₂
G ₀	44.56	45.28	46.35	42.21	43.50	44.46	43.39	44.39	45.41
G ₁	50.66	53.63	56.05	47.72	49.43	52.37	49.19	51.53	54.21
G ₂	49.71	52.64	54.76	46.92	49.18	51.49	48.32	50.91	53.13
G ₃	47.22	48.41	49.52	45.06	46.02	46.25	46.14	47.22	47.89
SE (m) ±	0.46			0.42			0.26		
CD at 5%	1.31			1.21			0.75		

Among the combinations, IAA @ 50 ppm with zinc @ 0.3% (G₁M₂) recorded the highest pooled grain yield (54.21 q/ha), followed closely by 6-BA @ 75 ppm with zinc (G₂M₂, 53.13 q/ha). The lowest yield was consistently observed in the control (G₀M₀, 43.39 q/ha) and PBZ-based combinations with or without micronutrients. The superior performance of PGR × zinc combinations can be attributed to the synergistic effect of hormonal regulation and micronutrient-assisted physiological processes. IAA enhanced panicle initiation, grain filling, and assimilate translocation, while 6-BA improved cytokinin-mediated spikelet fertility and tiller development. Zinc facilitated enzymatic activity, auxin metabolism, and nutrient mobilization, collectively increasing spikelet fertility, thousand-grain weight, and overall yield. Boron combinations improved yield moderately but were less effective than zinc-based interactions. These findings are in agreement with Pan *et al.* (2021) ^[10], Yogi *et al.* (2024) ^[19], and Renuka *et al.* (2024), who reported that the combined foliar application of IAA or 6-BA with zinc significantly increased rice grain yield by improving panicle number, spikelet fertility, chlorophyll content, and grain filling efficiency, highlighting the critical role of PGR × micronutrient synergy in maximizing rice productivity.

4. Conclusion

The present investigation clearly demonstrated that foliar application of plant growth regulators (PGRs) and micronutrients significantly improved yield attributes, grain yield, total biomass, and harvest index of rice (*Oryza sativa* L.) under high-rainfall lateritic soil conditions. Among the PGRs, IAA @ 50 ppm proved most effective, recording the highest spikelet fertility, grain yield per plant, grain yield per hectare, total biomass, and harvest index, followed closely by 6-BA @ 75 ppm. Application of PBZ @ 100 ppm increased panicle number but was comparatively less effective in improving spikelet fertility and grain yield. Among micronutrients, Zinc @ 0.3% consistently outperformed boron, significantly enhancing panicle number, spikelet fertility, grain yield, and biomass production. Importantly, the interaction effect revealed strong synergism between PGRs and micronutrients. The combination of IAA @ 50 ppm + Zinc @ 0.3% (G₁M₂) recorded the highest panicle number, spikelet fertility, grain yield per plant, total biomass, harvest index, and grain yield per hectare, followed by 6-BA @ 75 ppm + Zinc @ 0.3% (G₂M₂). Thus, foliar application of IAA (50 ppm) combined with Zinc (0.3%) at 60 and 80 DAS can be recommended as an effective and sustainable strategy to enhance rice productivity and harvest index under high-rainfall, micronutrient-deficient lateritic soils of the Konkan region.

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